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Mathematical Model of Wind Turbine Simulator Based Five-Phase Permanent Magnet Synchronous Generator with Nonlinear Loads and Harmonic Analysis

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ABSTRACT

This paper presents mathematical model of a wind turbine simulator based five-phase permanent magnet generator supplying nonlinear load. The mathematical model of wind turbine characteristics together with available tool blocks of the five-phase permanent generator and semiconductor devices of an AC-DC converter formed as a nonlinear load is implemented on MATLAB /Simulink to investigate the harmonic effect on performance of the generator. The detailed descriptions of the proposed model are fully given. The harmonic analysis is also provided. The validity of the proposed model is verified by simulation using MATLAB /Simulink in terms of dynamic responses of rotor speed, torque and power quality of the generator. It is found that the nonlinear load significantly affects the electromagnetic torque ripple and the distortions of both voltage and current of the generator. Moreover, the proposed system offers higher nonlinear load voltage and faster response compared to a conventional three-phase permanent magnet synchronous generator system. The electromagnetic torque ripple is reduced by 88% and the total harmonic distortions of the phase voltage and the stator current are more or less 7 % and 60 % which exceed the limits of the harmonic standards.

1. Introduction

Wind energy is one of the abundant renewable resources that is getting much attention around the world since it is clean, naturally occurring and environmentally friendly energy without burning fossil. In a wind turbine power generation system, the kinetic energy generated by the wind power is converted into mechanical torque at the shaft of the wind turbine which is coupled either directly or indirectly via gear box to the generator. Then the generator converts mechanical energy harvested from the wind energy by the turbine into electrical energy through magnetic field. However, the use of a wind turbine power generation system is necessary to study many components such as potential of locally generated wind speeds, electricity standards and regulations, system performance, expense and payback on investments, etc. In order to obtain the best performance of the system in terms of maximum efficiency achievement and cost-effectiveness, several research works and development of the wind turbine power generation systems have been paid attention [1,2]. Although an induction generator (IG) has various advantages over a major counterpart permanent magnet synchronous generator (PMSG), particularly for low maintenance, high ruggedness, and low cost, it gives lower efficiency and draws reactive power resulting in poor power factor for both self-excited and grid connected applications. Performance of a three-phase self-excited induction generator (SEIG) operating as a single-phase generator supplying nonlinear loads for standalone applications was investigated in [1]. However, the electromagnetic torque ripple due to harmonic effect has not been reported yet. Normally the SEIG needs a capacitor bank for reactive compensation for both voltage buildup process and voltage regulation but it significantly affects a variation of the generator frequency which is a drawback of the SEIG. Harmonic analysis and experimental tests of a three-phase SEIG with nonlinear loads were proposed in [3]. The obtained results confirm that the harmonics associated with the nonlinear loads affect the voltage and current waveforms. A PMSG is more attractive for small scale applications due to high efficiency, high power density, better voltage regulation for standalone applications [4]. Control of grid connection of an axial flux permanent magnet generator (AFPMG) (i.e. another type of PMSG) using a single-phase inverter with multifunctionality for real power transfer and reactive and harmonic compensations with various types of nonlinear loads was implemented in both simulation and hardware by [4,5]. However, the wind turbine simulator using motor drives as a prime mover has not been proposed. An example of a wind turbine

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simulator emulating actual wind turbine characteristics implemented by low cost hardware can be found in [6] which is useful in a laboratory test for wind energy conversion research. However, mathematical model of the simulator implemented on simulation was not focused. Unlike standalone applications, for grid connected applications, a large variation of the frequency of voltage and current of the generator is not necessary which is the major advantage of a wind turbine power generation system since an ac-dc rectifier converts alternating current into a direct current form. Generally, a five-phase permanent magnet synchronous machine is introduced in motoring operation rather than as a generator for electrical propulsion due to low torque pulsations, good fault tolerance, high power density and low loss [6-8]. Although the smaller ripple of the dc output voltage in the five-phase PMSG system associated with a rectifier than that in the three-phase PMSG system was presented in [9], harmonic effect on electromagnetic torque pulsation and harmonic analysis were not reported. There are a few publications related to performance evaluation of a five-phase PMSG with nonlinear load. Moreover so far the harmonic effect on the performance of the five-phase PMSG associated with wind energy conversion has not been investigated yet With the shortcomings of the previous works mentioned earlier, therefore this work contributes to mathematical model setup applied in simulation using MATLAB/Simulink computer program of the wind simulator based five-phase PMSG with nonlinear loads and harmonic analysis for investigating harmonic effect on the generator performance.

The paper is organized as follows. A wind power generation system is introduced briefly followed by mathematical model of wind turbine characteristics in Section 2. Section 3 describes mathematical model of the five-phase PMSG presented in a rotating d-q-x-y frame modeling followed by an available tool block in the MATLAB/Simulink. Section 4 deals with the nonlinear load model and harmonic analysis. Section 5 describes the proposed Simulink model and simulation results in terms of dynamic response and steady state conditions for various performances of the generator like terminal voltage and current waveforms, torque, speed, and so on together with discussion. Finally, conclusion and suggestion are given.

2. Wind Power Generation System

The electrical power generation system for grid connected applications used in the simulation is referred to Figure 1. It consists of a wind turbine simulator, a five-phase permanent magnet synchronous generator and a nonlinear load using a diode-based rectifier and a smoothing filter capacitor. Generally, an inverter circuit is used to convert DC input into AC output for grid connection in order to transfer the electrical energy produced from the wind energy to the grid. In the simulation, the model of the inverter is not taken into account. The equivalent resistor is used for representation of the transferred power and the converter power loss.

In steady state, the mechanical power generated at the shaft of the wind turbine can be obtained as [6]

$$P_{WT} = 0.5\rho\pi R^2 v_{wind}^3 C_p(\lambda, \beta) \tag{1}$$

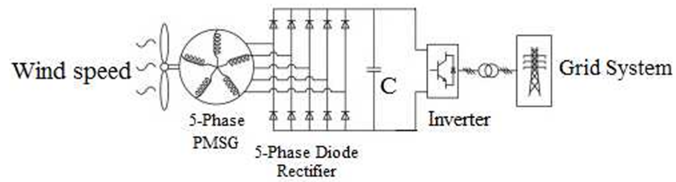


Figure 1: Overview of an electric power generation system using wind energy conversion system for grid connected applications.

where

P_{WT} is the mechanical power of the wind turbine ,

$\rho = 1.25\ kg/m^3$ which is the air density ,

R is the turbine rotor radius,

v_{wind} is the wind velocity,

C_p is the power coefficient,

β is the pitch angle, and

λ is the tip speed ratio.

The power coefficient is given by:

$$C_P(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4 e^{\frac{-C_5}{\lambda_i}}\right) + C_6\lambda \tag{2}$$

and

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The coefficients C_1 to C_6 are as follows. C_1 *is* 0.5176 , C_2 *is* 116 , C_3 *is* 0.4 , C_4 *is* 5 , C_5 *is* 21 and C_6 *is* 0.0068.

The tip speed ratio is given by:

$$\lambda = \frac{\pi n R}{30 v_{wind}} \tag{4}$$

The shaft torque of the wind turbine is expressed as

$$T_{WT} = \frac{30 P_{WT}}{\pi n} \tag{5}$$

where T_{WT} is the mechanical torque of the wind turbine and n is the rotor speed of the wind turbine. Schematic diagram of the proposed system for the simulation on a computer program is shown in Figure 2 in accordance with Figure 1. The power transferred to the grid and the converter power loss are lumped together represented by resistance R_{eq}. Figure 3 shows the simulation model implemented on MATLAB/Simulink simulation program as a wind turbine simulator. The mathematical expressions in (1)-(5) are used to generate wind turbine characteristics providing the mechanical torque applied to the PMSG tool block model. Detailed parameter values can be found in [6]. The wind turbine characteristics are plotted by using the wind turbine simulator as shown in Figures 4 and 5 for input mechanical torque and mechanical power against the rotor speed, respectively. As can be seen, below maximum values, the mechanical torque is proportional to the squared rotor speed whilst the mechanical power is proportional to the cube of the rotor speed at a given wind speed.

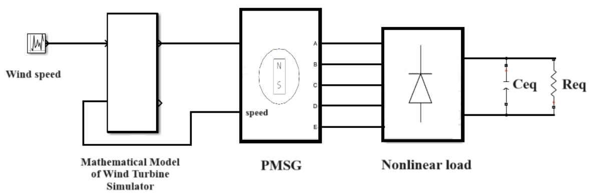


Figure 2: Schematic Diagram of wind turbine simulator based five-phase permanent magnet synchronous generator with nonlinear load.

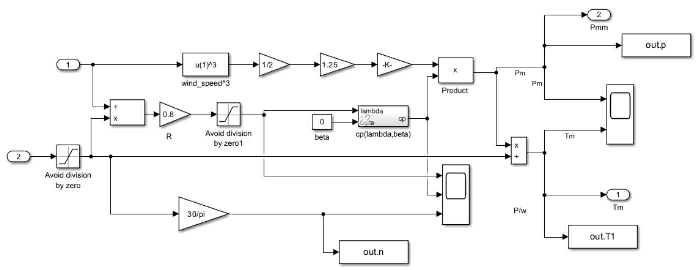


Figure 3: Mathematical model of wind simulator using MATLAB/SIMULINK

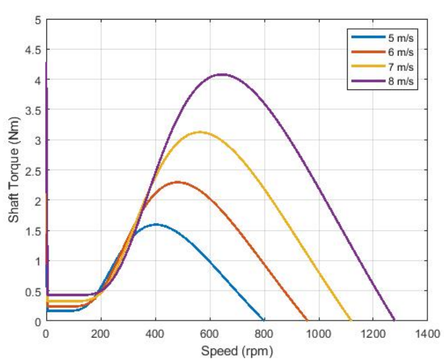


Figure 4: Applied mechanical shaft torque versus rotor speed with variation of wind speed

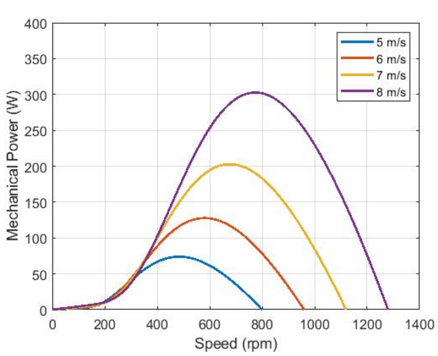


Figure 5: Applied mechanical power against rotor speed with variation of wind speed.

The results from Figures 4 and 5 are in accordance with [6]. Theses confirm the validity of the proposed wind turbine simulator in a mathematical model form.

3. Five-Phase Permanent Magnet Synchronous Generator

The stator winding for each phase is displaced by 72 electrical degrees. The 5-phase PMSG can be modeled in a rotating d-q-x-y frame for analysis of dynamic response and steady state conditions [6]. More details can be also found in [7], [8] and [10]. The mathematical equations can be expressed as follows.

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (6)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \phi_f \quad (7)$$

$$v_x = R_s i_x + L_{ls} \frac{di_x}{dt} \quad (8)$$

$$v_y = R_s i_y + L_{ls} \frac{di_y}{dt} \quad (9)$$

$$v_o = R_s i_o + L_{ls} \frac{di_o}{dt} \quad (10)$$

The relationship between the mechanical torque (T_l) and the electromechanical torque (T_{em}) can be given as

$$J\frac{d\Omega}{dt} + f_r \Omega = T_{em} - T_l \quad (11)$$

where v_d, v_q, v_x, v_y, i_d , i_q, i_x, i_y are the stator voltages and stator currents in the d-q-x-y, respectively. J is the moment of inertia, f_r is the viscous coefficient, and Ω is the rotor speed and T_l is the load torque.

The electromagnetic torque can be expressed as

$$T_{em} = \frac{5}{2} p\left(\phi_f i_q - \left(L_d - L_q\right) i_d i_q\right) \quad (12)$$

where p is the pole pair, L_d is the direct axis inductance, L_q is the quadrature axis inductance, i_q is the quadrature axis current, i_d is the direct axis current, L_{ls} is the leakage inductance and ϕ_f is the flux generated by permanent magnet in the rotor. These equations are used for calculation in the machine model. The available tool block for the PMSG model in MATLAB/SIMULINK is illustrated in Figure 6. T_m is the input mechanical torque which the positive sign is for the motoring operation and negative sign represents the generator operation. “m” is the output for measuring various variables and machine performance like stator currents, flux linkages, and mechanical outputs such as speed, electromagnetic torque, etc. The rated values of the used model of the 5-phase PMSG are output torque of 8 Nm and the rotor speed of 2000 RPM.

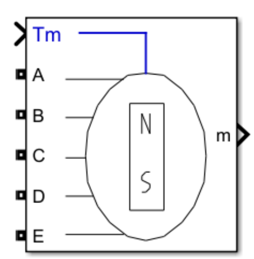


Figure 6: Tool block model of a five-phase permanent magnet synchronous generator available in MATLAB/ Simulink.

4. Nonlinear Load model and Harmonic Current Analysis

In this work, the nonlinear load is connected in parallel with the generator output consisting of a five-phase full bridge rectifier including 10 diodes and a smoothing filter capacitor connected in parallel at the output of the rectifier. The per phase simplified model of the PMSG with nonlinear load is shown in Figure 7 which various harmonic currents produced by the nonlinear load are represented by harmonic current sources. The time domain of harmonic currents can be expressed as

$$i_s(t) = \sum_{n=1}^{\infty} I_n \cos(n\omega t - \theta_n) \tag{13}$$

where I_n is the amplitude of the source current at harmonic order n and θ_n is the phase difference angle of the current with respect to the source voltage. The nonlinear load model in [11] with Matlab/Simulink is shown in Figure 8 where R_{eq} represents the converter loss and the active power drawn by the grid system in accordance with Figure 1. The values of the smoothing filter capacitor and R_{eq} are $5000\ \mu F$ and $10\ \Omega$ respectively. The diode model consists of a RC snubber circuit including R_s of $250\ \Omega$, connected in series with C of $250\ nF$, forward voltage drops of 0.8 V and conduction resistance (R_{on}) of $0.001\ \Omega$. In order to analyze the propagation of a harmonic source in the PMSG, the simplified equivalent circuit can be depicted as shown in Figure 9 which is treated in the same manner as the circuit reported in [12] for a three-phase SEIG. The transfer function of the harmonic current propagation can be expressed as

$$T(s) = \frac{I_{mh}}{I_h} \tag{14}$$

By using KCL (Kirchoff's current law), the harmonic current at order h injected into the machine yields

$$I_{mh} = \frac{R_L}{R_L + R_s + sL_s} I_h \tag{15}$$

In this study, the parameters of the PMSG are as follows. R_s is $0.0485\ \Omega$, L_s is $8.5\ mH$ and R_L is 10Ω. Therefore, the transfer function of the harmonic propagation is

$$T(s) = \frac{I_{mh}}{I_h} = \frac{R_L}{R_L + R_s + sL_s} = \frac{10}{0.0085s + 10.0485} \tag{16}$$

From (16) the frequency response can be illustrated in magnitude and phase forms by using the Bode Plot as shown in Figure 10. According to these results the cut-off frequency is approximately 100 kHz. It implies that the harmonic frequency below this value can affect the PMSG. Note that the harmonic currents can give the effect of a decrease in efficiency, heating and reducing the lifetime of the machine [12].

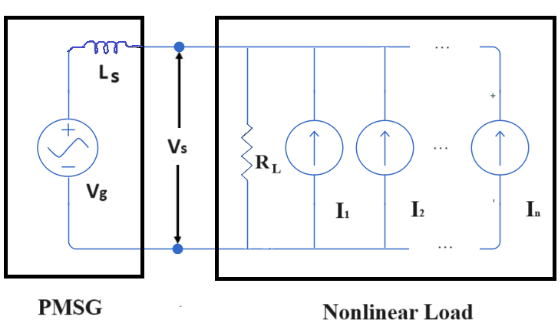


Figure 7: Simplified model of PMSG considering nonlinear load.

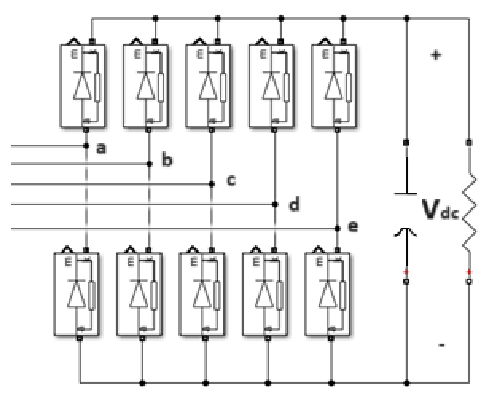


Figure 8: Model of the nonlinear load using MATLAB/ Simulink.

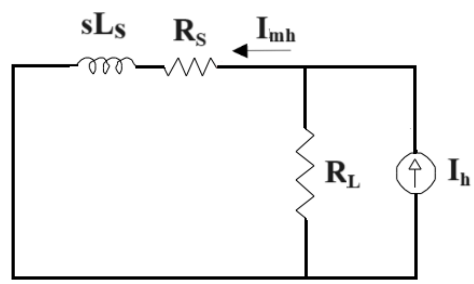


Figure 9: Simplified equivalent circuit for considering harmonic current propagation on PMSG.

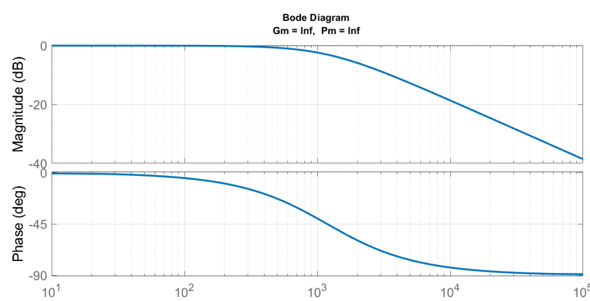


Figure 10: Frequency response for harmonic current propagation.

5. Simulation Results and Discussion

The simulation model of the wind turbine simulator based five- phase PMSG supplying nonlinear load is implemented by using MATLAB/SIMULINK as shown in Figure 11. It consists of a five-phase PMSG tool block and subsystems of the wind turbine simulator using the proposed mathematical model, and the nonlinear load. Wind speed is required for the command. The wind turbine simulator provides the input mechanical torque for the PMSG. The rotor speed of the PMSG is used to feedback to the wind simulator. Various waveforms and signals are measured by measurement units.

Figure 12 illustrates comparative waveforms between the conventional three-phase PMSG and the proposed five-phase PMSG of the machine terminal voltage and nonlinear load voltage (i.e. dc link voltage or output of the rectifier, Vdc) at the wind speed of 6 m/s during startup and steady state conditions.

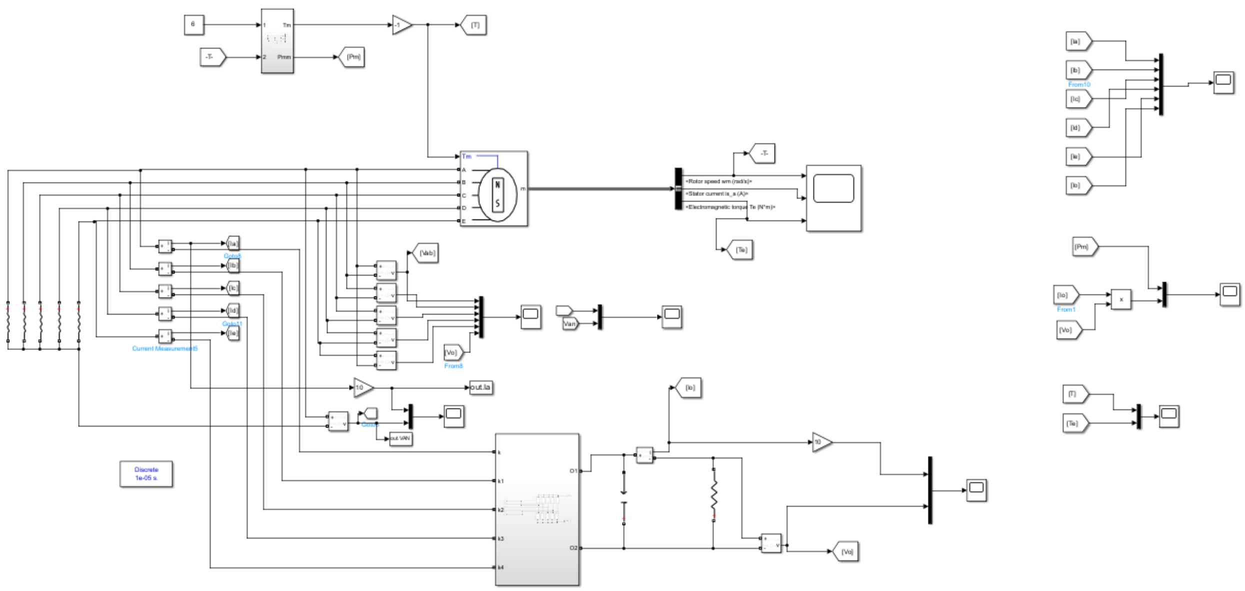
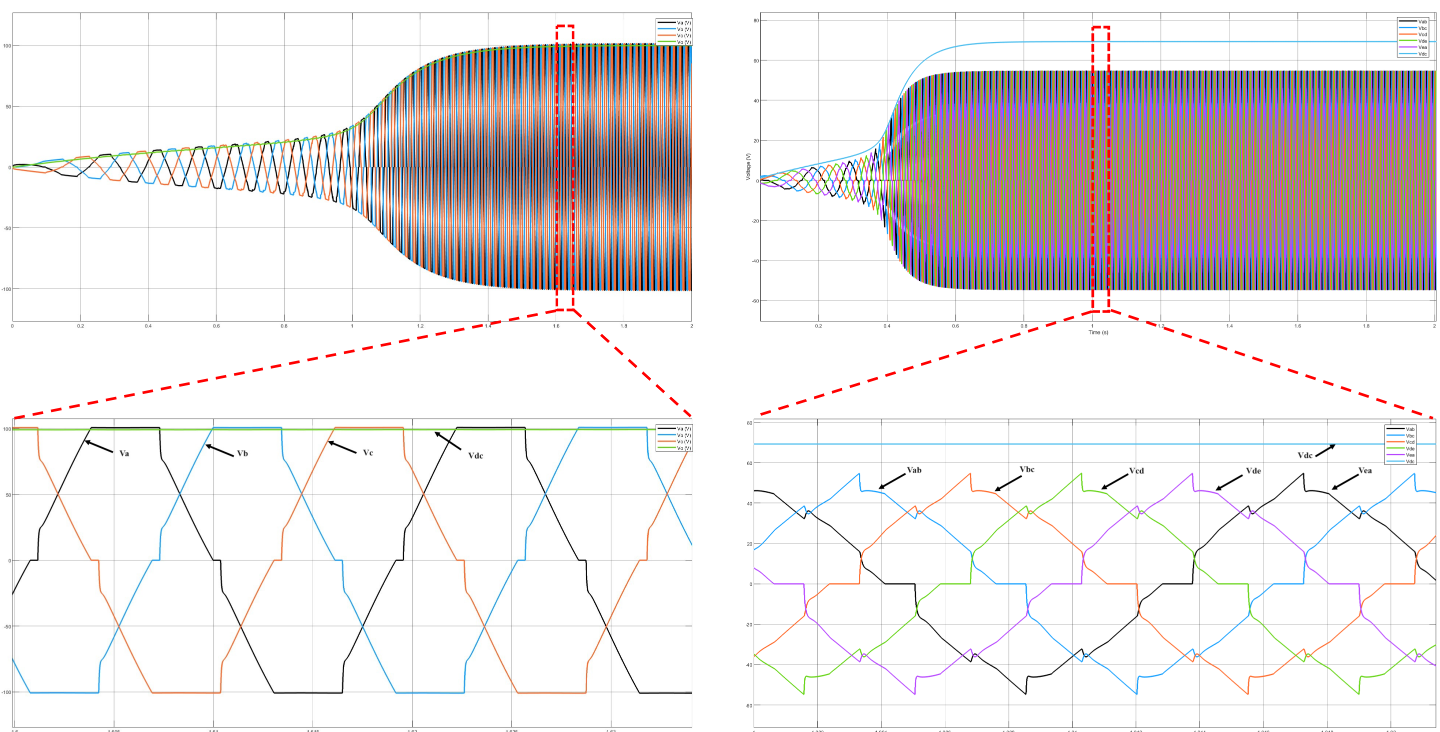


Figure 11: Simulation model of wind turbine simulator based five-phase PMSG.



a.)

b.)

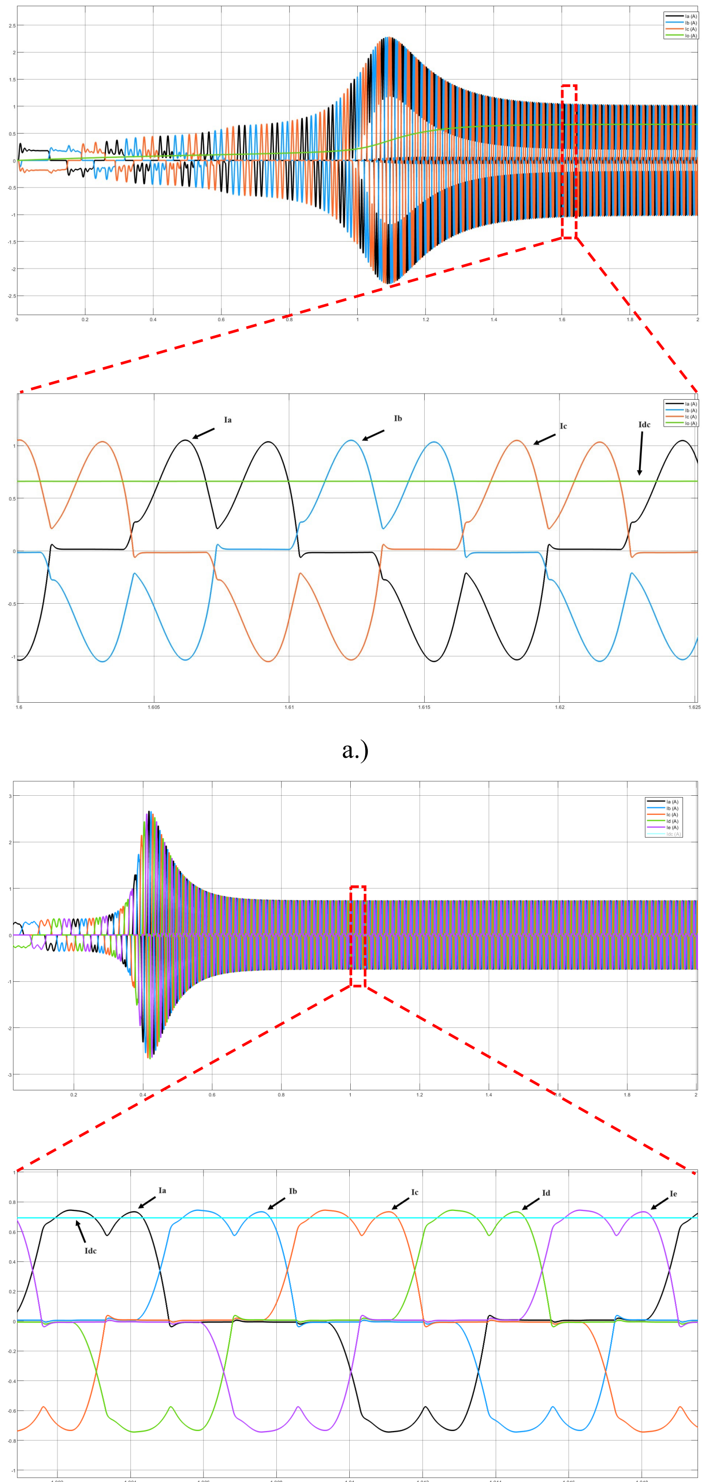
Figure 12: Waveforms of output voltage of rectifier and terminal voltage during startup and steady state conditions and corresponding enlarged waveforms a.) conventional three-phase PMSG b.) proposed five-phase PMSG

Clearly, with the same input mechanical torque for both cases the voltage and its frequency are gradually increased and then abruptly grown up until steady state. The dc output voltage of the rectifier and dynamic response for the proposed PMSG are higher and faster response than those for the conventional three-phase PMSG, respectively. The enlarged waveforms show the distortion due to the propagation of the harmonic currents associated with the nonlinear load. The dc voltage of the rectifier output is much higher than the peak value of the terminal voltage which is the advantage of the proposed five-phase PMSG compared to the conventional three-phase PMSG. Moreover, the dc output contains insignificant ripple. Apparently, enlarged waveforms of the terminal voltages are distorted from sinusoid due to the propagation of the harmonic currents associated with the nonlinear load for both cases. The five-phase PMSG with nonlinear load offers less distortion of voltage waveforms than those for the three-phase PMSG. Figure 13 illustrates comparative waveforms between the conventional three-phase PMSG and the proposed five-phase PMSG of the corresponding stator currents and dc output current waveform during start up and steady state conditions. The dc output current of the rectifier and dynamic response for the proposed PMSG are higher and faster response than those for the conventional three-phase PMSG, respectively. Obviously, the inrush currents are present during a suddenly increase in terminal voltage for both cases. Apparently, the enlarged current waveforms are distorted due to the nonlinear load.

Figures 14 and 15 show dynamic response during startup of the input mechanical torque and the electromechanical torque of the PMSG for linear and nonlinear loads with the same condition for a conventional three-phase PMSG and the proposed five-phase PMSG, respectively. Noticeably, the electromagnetic torque contains higher ripple and slower response for the nonlinear load compared to the linear load due to the large value of the smoothing filter capacitor and harmonic effect. When comparing the ripple of the electromagnetic torque and dynamic response for the nonlinear load between the conventional three-phase PMSG and the proposed five-phase PMSG, obviously, the proposed five-phase PMSG has lower ripple and faster response than the three-phase PMSG. During the growth of the terminal voltage, the transient torque occurs for both linear and nonlinear loads. The peak values of the mechanic torque for both cases are almost equal. The significant difference between the input mechanical torque and the electromagnetic torque during transient response represents the large acceleration torque required for the linear load resulting in faster response (i.e. see equation (11). At the steady state, the absolute input mechanical torque is little higher than the absolute electromagnetic torque due to friction and windage components.

Figures 16 and 17 illustrate the enlarged waveforms during the steady state of the input mechanical torque and the electromagnetic torque for linear and nonlinear loads. Clearly, the electromagnetic torque has higher ripple for the nonlinear load than that for the linear load. It is found that the electromagnetic torque ripple is about 9.34% which is in good agreement with [9]. Note that the electromagnetic torque ripple for the five-phase PMSG is lower than that for the conventional three-phase PMSG reported in [9]. The peak-to-peak electromagnetic torque ripple of the proposed five-phase PMSG is reduced about 88.18%. compared to that of the conventional three-phase PMSG. In order to confirm the higher ripple of the electromagnetic torque for the conventional three-phase PMSG with nonlinear load, Figure 18 illustrates comparative harmonic spectra of the electromagnetic torque between the three-phase PMSG and the proposed PMSG by using FFT analysis tool block. Obviously, the electromagnetic torque of the conventional three-phase PMSG contains large low order harmonic components (i.e. the sixth hramonics) resulting in high pulsation.

Figure 19 shows the input mechanical power and the electrical power of the nonlinear load. During transient response in startup duration the input power is drastically higher than the output power since the input power is drawn with large amount for acceleration of the generator. Eventually, the input power is higher than the output power with a fixed value. The difference of both powers is present due to the machine losses including core loss, copper loss, and friction and windage loss, semiconductor losses including conduction and switching losses, and snubber loss in the model. As a consequence, it implies that the efficiency of the system can be determined which is not included in here. Comparison between linear and nonlinear loads for phase voltage and current waveforms are shown in Figure 20.



a.)

b.)

Figure 13: Waveforms of stator currents during start up and steady conditions and enlarged waveforms
a.) conventional three-phase PMSG b.) proposed five-phase PMSG

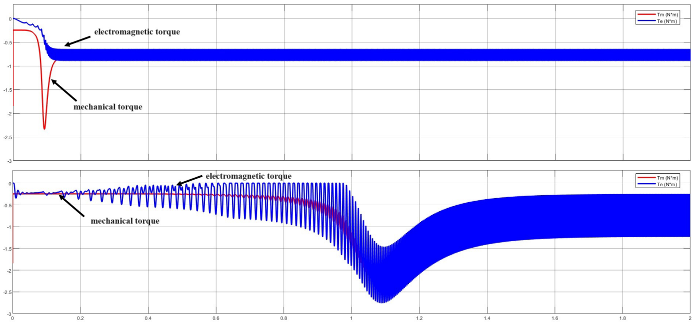


Figure 14: Input mechanical torque and electromagnetic torque of conventional three-phase PMSG a.) linear load b.) nonlinear load

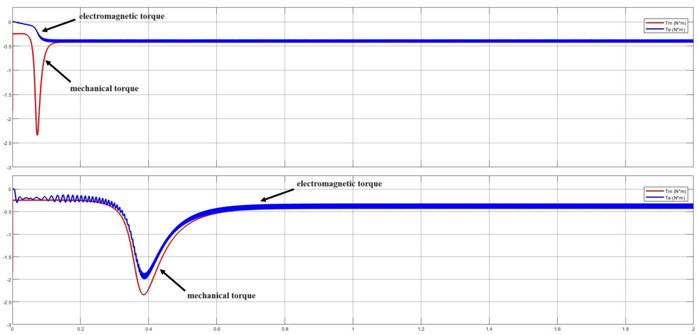


Figure 15: Input mechanical torque and electromagnetic torque of the proposed five-phase PMSG a.) linear load b.) nonlinear load

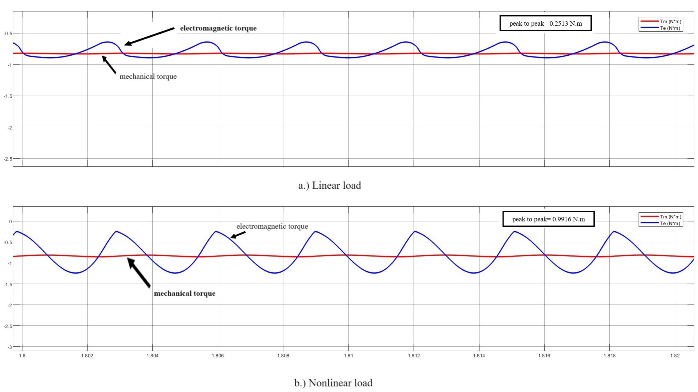


Figure 16: Instantaneous input mechanical torque (red signal) and instantaneous electromagnetic torque (blue signal) under steady state of conventional three-phase PMSG.

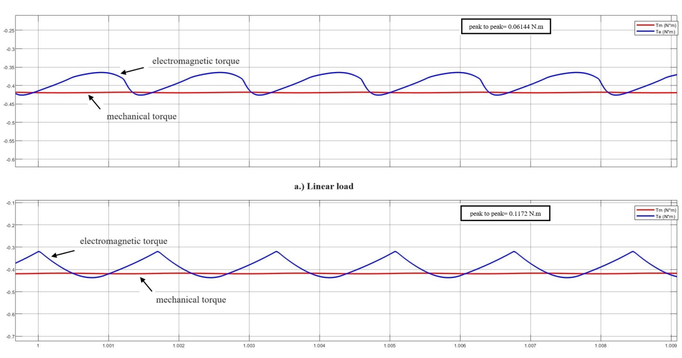


Figure 17: Instantaneous input mechanical torque (red signal) and instantaneous electromagnetic torque (blue signal) under steady state of the proposed five-phase PMSG.

Apparently, unlike for linear load without distortion, both terminal voltage and stator current waveforms of the generator for the nonlinear load are significantly distorted from sinusoidal waveforms. This is the fact that the harmonic currents associated with the nonlinear load are injected to the machine resulting in the distortion of sinusoidal waveforms.

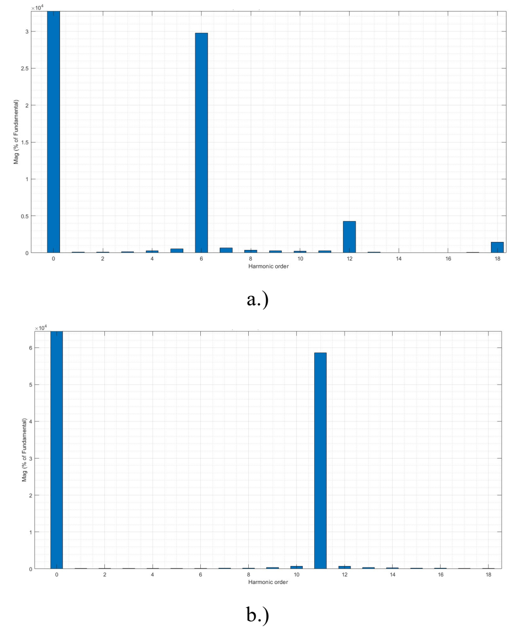


Figure 18: Electromagnetic torque spectra for nonlinear load a.) conventional three-phase PMSG b.) proposed five-phase PMSG

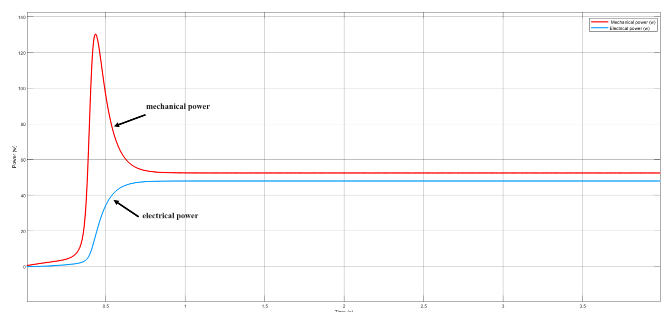


Figure 19: Transient response and steady state conditions during startup of input mechanical power and the output electrical power of the nonlinear load.

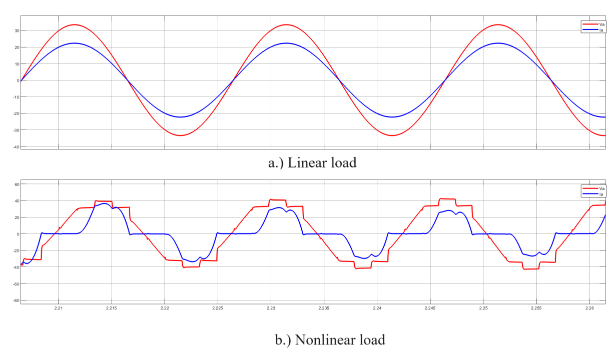
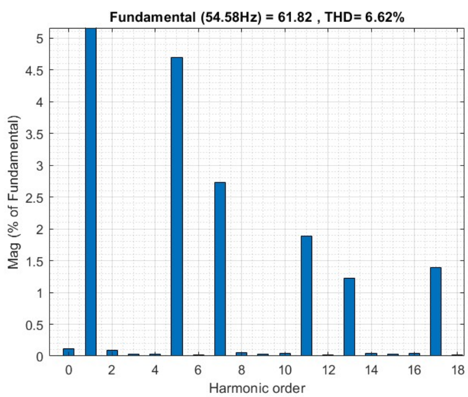
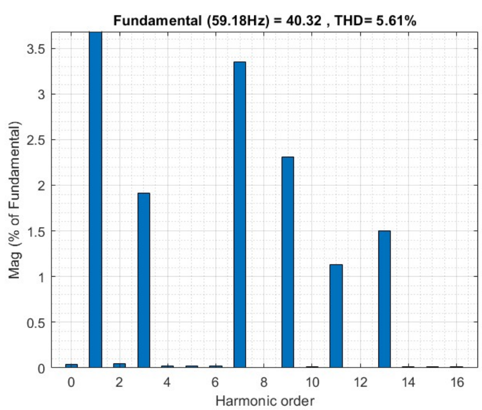


Figure 20: Terminal voltage and stator current waveforms for nonlinear load and linear load.

Figures 21 and 22 illustrate comparative harmonic spectra of both terminal voltages and stator currents between the three-phase PMSG and the proposed PMSG for the nonlinear load by using FFT analysis tool block. For the proposed PMSG case, the total harmonic distortion of the phase voltage and stator current are more or less 7 % and 60 % , respectively. These high figures are not within acceptable levels, particularly for the current case [13]. The solution for this problem could be introduced by either passive or active power filters. Note that these values depend on load level conditions. Quite clearly, unlike the conventional PMSG, the magnitudes of the third harmonics for both current and voltage are dominant. Unlike the conventional three-phase PMSG, some multiples of three of harmonics are still present which are different from a three-phase system in which the multiples of three of harmonic orders are absent. As a consequence, the harmonic distortion for the conventional three-phase PMSG is better than that for the proposed PMSG. The harmonic orders are in agreement with those reported in [14-17].



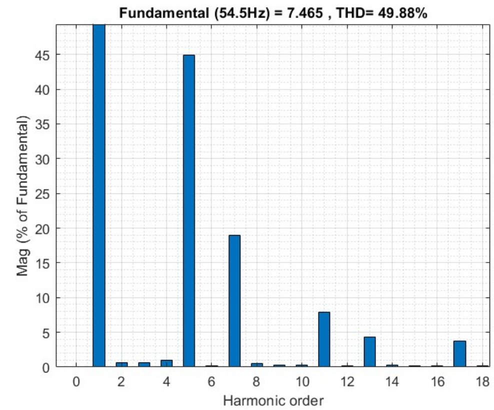
a.)



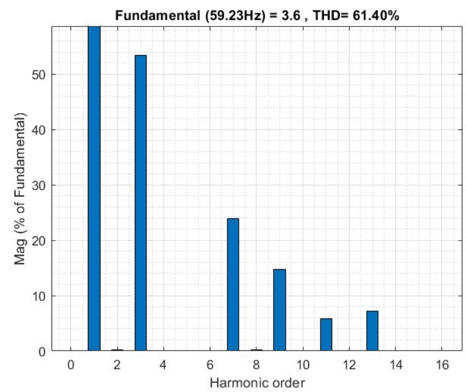
b.)

Figure 21: Terminal voltage harmonic spectra for nonlinear load
a.) conventional three-phase PMSG b.) proposed five-phase PMSG

Figure 23 show a comparison of the ripple of the dc output voltage for the nonlinear load between the conventional three-phase PMSG and the proposed five-phase PMSG. Obviously, unlike the conventional three-phase PMSG, the ripple exists twice frequency of the ac terminal voltage of the machine. As a result, the proposed five-phase PMSG has lower ripple of dc output voltage lower than three-phase PMSG. It implies that the proposed five-phase PMSG requires a smaller size of the smoothing capacitor.

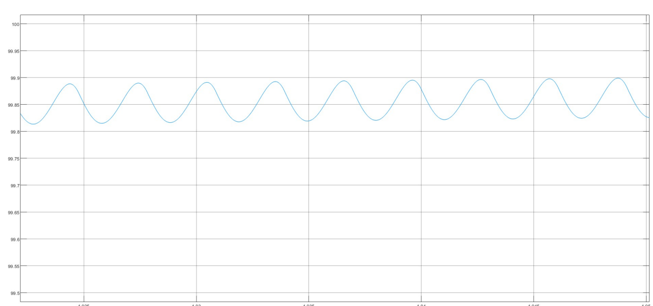


a.)

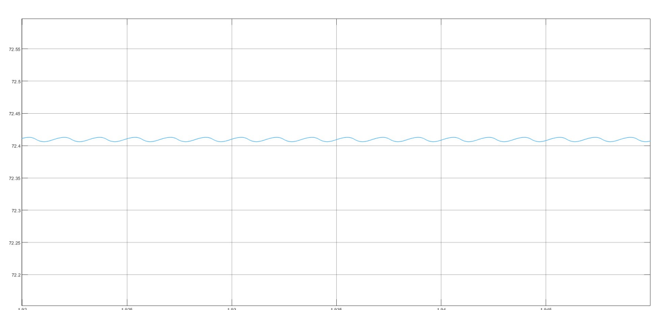


b.)

Figure 22: Stator current harmonic spectra for nonlinear load
a.) conventional three-phase PMSG b.) proposed five-phase PMSG



a.)



b.)

Figure 23: Ripple voltage of the DC output voltage with nonlinear load
a.) conventional three-phase PMSG b.) proposed five-phase PMSG

Figure 24 displays transient responses of the rotor speed, the stator phase current and the electromagnetic torque during a step change in wind speed from 5 to 8 m/s at t=2 seconds. At the beginning of the startup operation, the rotor speed, the electromagnetic torque (i.e. negative sign), and the stator current and its frequency are gradually increased. Then at about t=0.5 seconds, they are rapidly grown up until they reach to the steady state. When the wind speed is changed in a step, the high peak electromagnetic torque and high inrush stator current occur. Obviously after transient response the electromagnetic torque and stator current fall down to steady state values which are higher than the previous ones before disturbance. The rotor speed is increased slowly which looks like the response of the first order of a derivative equation in accordance with (11).

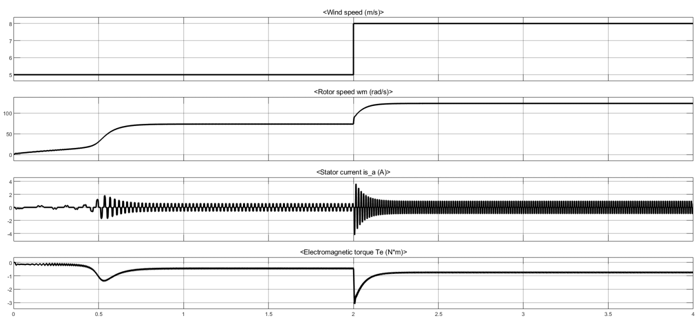


Figure 24: Step change in wind speed from 5 m/s to 8 m/s

In order to investigate the performance of the proposed system during wind speed changes according to the realistic conditions, wind speeds with random input ranging between 5 to 8 m/s, have been applied. The dynamic responses of the rotor speed, the electromagnetic torque and stator current with such random wind speeds are illustrated in Figure 25. The rotor speed response is slower than the wind speed command. The final value of the rotor speed after disturbance is promotional to the wind speed. During a step change in either an increase or a decrease in the wind speed, the high inrush current and high peak torque occur particularly during startup.

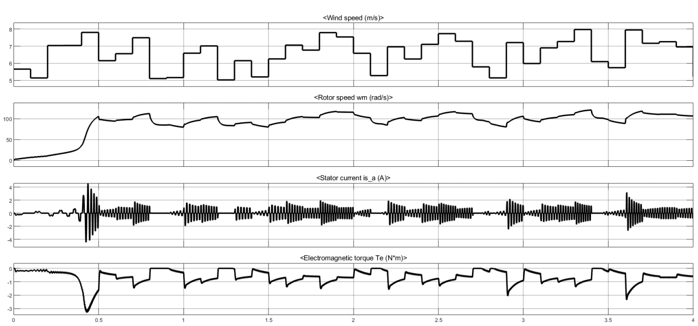


Figure 25: Dynamic response for random input wind speed for the nonlinear load.

6. Conclusion

This paper has proposed mathematical model of a wind turbine simulator based five-phase permanent synchronous generator supplying nonlinear load using MATLAB/Simulink. The related mathematical equations of the machine model are also described. The harmonic analysis for propagation and the harmonic effect on the PMSG have been given. The descriptions of Simulink model of the proposed system are fully given. The investigation of the performance and power quality of the PMSG with the nonlinear load under various conditions has been conducted. It is found that the harmonics associated with the nonlinear load adversely affects the performance and power quality of the PMSG. The nonlinear load causes degradation of the performances of the proposed PMSG in terms of higher electromagnetic torque ripple and slower response when compared to the linear load case. The proposed five-phase PMSG offers some advantages over the conventional three-phase PMSG in terms of lower electromagnetic torque, higher output dc voltage value and lower ripple of the dc output voltage. However, its disadvantage is higher harmonic distortions of both terminal voltage and stator current which are over limits of the standards. The suggestion is a requirement of harmonic solutions such as either passive or active power filters to mitigation of such harmonics.

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